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Compressive Strength of Steel-Fiber Concrete with Artificial Lightweight Aggregate (ALWA)

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Abstract

In the last decade, there have been many innovations developed to replace the aggregate as material for concrete, particularly the coarse aggregate using the artificial lightweight aggregates a.k.a. ALWA. In the study, the main ingredient used to develop the artificial lightweight aggregates is the styrofoam. Styrofoam has a lightweight characteristic so that it can reduce the density of the concrete. If the density of the concrete can be lighter than the normal-weight concrete then the overall weight of the structure of a building will also be lighter. Thus, the shear force due to the earthquake will also be smaller so that the safety of the building becomes better. The styrofoam used was dissolved with the acetone solution and formed into granules in which the size resembled the coarse aggregate size of about 10 to 20 mm. The styrofoam which has been formed then dried up so that the texture becomes hard. In addition, steel fiber was also used as an added ingredient in concrete mixtures so that the concrete was highly resistant against cracking and was expected to increase the compressive strength of the concrete. ALWA compositions used to replace coarse aggregates were 0%, 15%, 50%, and 100%. While the composition of steel fiber used was 0%, 0.75%, and 1.5% of the total volume of the cylinder. The type of steel fiber used was hooked-end steel fiber with the diameter and the length of 0.8 mm and 60 mm, respectively. The results showed that the concrete with 15% styrofoam ALWA and 1.5% of steel fiber were able to produce optimum compressive strength by 28.5 MPa and the modulus of elasticity by 23,495 MPa. In addition, the use of Styrofoam ALWA as a substitution to the coarse aggregate can reduce the density of concrete as much as 5 to 35%.

Keywords: Artificial Lightweight Aggregate (ALWA); Compressive Strength; Density; Modulus of Elasticity; Steel Fibers; Styrofoam.

1. Introduction

Concrete has been used in the past few decades and becoming the most popular material for constructing various kinds and needs of structural members [1-3]. Due to the high demands on concrete in construction, hence it will also require the basic forming materials for concrete such as natural coarse aggregate. The natural materials are not renewable and it will once disappear from the earth due to extremely excessive exploration of natural resources such as the natural coarse aggregate. Thus, it certainly require a need to come up with innovative solution such as the artificial aggregate to replace to the natural one. Innovation to create the artificial aggregate has been developed for many years [4-7]. This is one of the promising solutions on the near future issue that is when the natural aggregate availability from the nature is getting scarce or difficult to obtain [8, 9]. The coarse aggregate is one of the aggregates (fine and course) that can be replaced with the artificial one. If the material used to produce the aggregate has a lightweight characteristic it can be called as artificial lightweight aggregate (ALWA) [8, 9].

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One purpose of using the artificial lightweight aggregate (ALWA) is to make the lightweight concrete as it reduces the density of the concrete. The use of the artificial lightweight aggregate (ALWA) that meets the structural concrete requirements will affect the design as it will affect the dimensions of the main components of the structural buildings such as columns and beams [10, 11]. In addition, if the weight of the concrete becomes lighter, then the weight of the structure of a building will also be lighter and the earthquake shear force will be lesser so that the safety of the building becomes higher [12, 13]. The innovation of using the artificial lightweight aggregate (ALWA) as the replacement of the heavier natural coarse aggregate lead to the lighter structures, thus lower earthquake forces in the structures, and further reduces the risk of seismic hazard [14, 15]. This is suitable for structures in the highly-seismic risk regions [16, 17]. The materials used to make artificial lightweight aggregate (ALWA) are not only come from the nature, but from other materials as well, such as the styrofoam waste.

The styrofoam used is classified into the EPS (expanded polystyrene) type. EPS is composed of 98% air and 2% polystyrene. The styrofoam is widely used as containers of electronic products, food packing, etc. The styrofoam is one of the trashes which are the most difficult one to unraveled and its presence will continue to accumulate in the future. It will have a big impact on the environmental pollution [18]. One effort to increase the usage value of the styrofoam is by adopting it for the concrete mixture (for artificial lightweight aggregate (ALWA) to replace the natural coarse aggregate).

The application of styrofoam as a replacement of the coarse aggregate in concrete has been studied earlier [19-21]. It was found that the more the amount of styrofoam used in concrete, the compressive strength of concrete decreases. In this study, in order to maximize the use of styrofoam as an ingredient in making the artificial lightweight aggregate (ALWA) for substitution of the coarse aggregate, it was dissolved by the acetone solvent (CH3COCH3) and then formed into granules with the size resembling the coarse aggregate size and further dried up to form harder texture of artificial aggregate.

In addition, steel fibers are also used as additives for concrete mixtures. The use of steel fibers is to improve the resistance of the concrete from cracking so that the compressive strength of the concrete increases [22-24]. The study that relates to the use of steel fibers in concrete mixtures states that with the addition of 1.5% of steel fibers capable of producing the maximum compressive strength of concrete [25-27].

2. Research Methodology

2.1. Material

Materials used in this research are cement and steel fibers. The cement used in this research is Type I cement, PPC (Portland Pozzolana Cement) ASTM C595/C595M-18 [28]. The steel fiber used in this study is hooked end type. The steel fiber shape can be seen in Figure 1. The length of steel fiber is 60 mm and its diameter is 0.8 mm (l/d = 75 mm). The dimensions and tensile strength of steel fibers are given in Table 1.

Table 1. Dimension and tensile strength of steel fiber

Diameter (mm)	Length (mm)	Tensile strength (N/mm^2)	Aspect ratio, l/d
0.8	60	1254	75

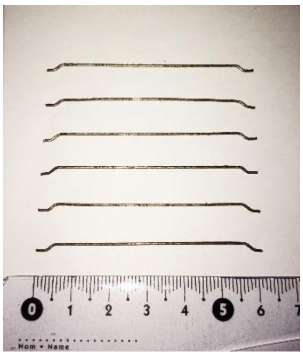

Figure 1. Shape of hooked-end steel fiber type

2.2. Aggregates

Aggregates used in this research are fine aggregates, coarse aggregates and Styrofoam artificial lightweight aggregate. The fine aggregate used was the black sand. According to the results of the sand's sieve analysis, it can be categorized into Gradation Zone II. Meanwhile, the coarse aggregate used in this research was the crushed stone with the maximum size of 20 mm. The physical properties of coarse and fine aggregates are listed in Table 2.

The main ingredient used to make artificial lightweight aggregate in the study was the styrofoam. The styrofoam used was from the industrial waste that was not recycled. The first step to produce the artificial lightweight aggregate was to dissolve the styrofoam with the acetone solution. The weight ratio between the styrofoam and acetone solution was 1:1.19. Acetone solution was mixed with the styrofoam until melted. ALWA from styrofoam was used as a substitution to the coarse aggregate. The melted styrofoam is then formed into granules with the size resembling the size of the coarse aggregate of 10 mm to 20 mm. Granules that have been made then was soaked in the water for 3 days until the texture of ALWA hardened. The hardened ALWA was then dried up as shown in Figure 2. The physical properties of ALWA styrofoam are given in Table 3.

Table 2. Physical properties of coarse and fine aggregates

Laboratory test	Fine aggregate	Coarse aggregate	Unit
Specific gravity	2.66	2.62	gram/cm^3
Unit weight	1475	1558	kg/m^3
Sieve analysis	Zone 2	Size 20 mm	-
Fine modulus	2.7	6.71	-
Fineness	3.52	0.47	%
Evaporable moisture content	4.28	0.74	%
Absorption	1.49	1.40	%

Table 3. Physical properties of styrofoam artificial lightweight aggregate

Laboratory test	Styrofoam ALWA	Unit
Specific gravity	0.71	gram/cm^3
Unit weight	423	kg/m^3
Sieve analysis	Size 20 mm	-
Fine Modulus	6.42	
Aggregate impact value (AIV)	2.66	%

Figure 2. Styrofoam ALWA

2.3. Mix Design of Concrete

Styrofoam ALWA was used as a substitution to the coarse aggregate. The composition of Styrofoam ALWA used was 0%, 15%, 50%, and 100%. Whereas, the composition of steel fiber used was 0%, 0.75%, and 1.5% by volume. The characteristics of styrofoam ALWA is light and does not absorb the water so that no adjustment of the water-cement ratio and remain as its initial value (0.3). The study included 12 compositions consisted of mixed between the styrofoam ALWA and steel fibers. Each composition consisted of 3 specimens. The specimens used for testing were the cylinders with the size of 100 mm × 200 mm. The number of specimens using styrofoam ALWA and steel fibers are given in Table 4 and The concrete composition from the mix design are given in Table 5.

Table 4. Number of specimens

Percentage of Styrofoam ALWA	Number of specimens		
	0% steel fiber	0.75% steel fiber	1.5% steel fiber
0%	3	3	3
15%	3	3	3
50%	3	3	3
100%	3	3	3

Table 5. Concrete composition from mix design

Percentage of Styrofoam ALWA	Material					Percentage of steel fiber			Unit
	Cement	Fine aggregate	Coarse aggregate	Styrofoam ALWA	Water	0% steel fiber	0.75% steel fiber	1.5% steel fiber	
0%	700	542	923	0	210	-	52.13	104.26	kg/m^3
15%	700	542	923	38	210	-	52.13	104.26	kg/m^3
50%	700	542	923	125	210	-	52.13	104.26	kg/m^3
100%	700	542	923	251	210	-	52.13	104.26	kg/m^3

2.4. Testing Method and Data Measuring System

The concrete cylinder tests were performed after the age of concrete reached 28 days. The tests performed were the compressive strength and the modulus of elasticity tests. The compressive strength test refers to the ASTM C39/C39M-18 [29]. The machine used for compressive strength testing is the Universal Testing Machine (UTM) HT-2101 with the maximum capacity of 2000 kN. The machine was capable of producing not only the maximum compressive strength of concrete, but also capable of providing the stress and strain values such that the modulus of elasticity of the concrete can be calculated. Load cell and transducer were used to measure the load and displacement, respectively. The data was read by the data logger and transferred to the computer for recording.

3. Result and Discussion

3.1. Slump Test Result

The purpose of slump test is to measure the degree of slump of the fresh concrete and thus, the workability. The results of slump tests are given in Table 6.

Table 6. Slump test results

Percentage of Styrofoam ALWA	Slump value (mm)		
	0% steel fiber	0.75% steel fiber	1.5% steel fiber
0%	42	35	30
15%	45	40	35
50%	50	46	36
100%	55	48	40

The target or designed slump value ranges from 30 to 60 mm. Based on the test results, it can be seen that the slump value measured from the fresh concrete did not exceed the designed slump value. Concrete mixtures using ALWA Styrofoam without the addition of steel fibers increased the slump value. This is due to the reason that the styrofoam ALWA did not absorb the water. Therefore, the water was absorbed by the other concrete materials. The more Styrofoam ALWA used as a substitution to the coarse aggregate, the lighter the result of the concrete mixture. This certainly improved the workability of the concrete.

Concrete mixtures using a combination of styrofoam ALWA and steel fibers decreased the slump value. The more steel fiber used in the mixture, the lower its slump value. The addition of steel fibers to concrete mixture resulted in increasingly difficult workability level. However, the more styrofoam ALWA introduced in the concrete mixture, the lighter it is such that the workability is higher. In addition, to facilitate the application of the steel fiber, the mixing process used the wet method. The wet method is used to ease in spreading up the steel fiber that is after the introduction of the mixing water in the concrete mixture. This method was carried during the concrete mixing process to prevent the fiber from clumping (a.k.a. the balling effect).

3.2. Density of Concrete

Styrofoam ALWA has a lightweight characteristic such that it is one of the objective and important to find the influence the use of styrofoam ALWA in reducing the density of concrete. The density of concrete measured with variation of styrofoam ALWA can be seen in Table 7. The relationship between percentage of styrofoam ALWA and density of concrete is shown in Figure 3.

Table 7. Density of concrete

Percentage of Styrofoam ALWA	Density of concrete (kg/m^3)		
	0% steel fiber	0.75% steel fiber	1.5% steel fiber
0%	2472.2	2493.4	2509.3
15%	2329.0	2344.9	2355.5
50%	2016.0	2026.6	2084.9
100%	1607.5	1819.7	1840.9

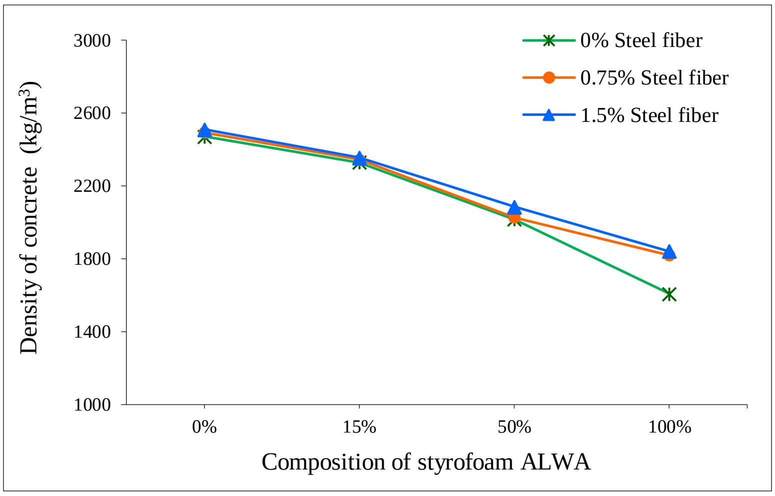

Figure 3. The relationship between percentage of styrofoam ALWA and density of concrete

Styrofoam ALWA used as a substitution to the coarse aggregate can reduce the density of concrete. The use of styrofoam ALWA of 15%, 50%, and 100% without the addition of steel fiber can reduce the density of concrete as much as 6%, 18%, and 35%, respectively, of the normal concrete. The use of styrofoam ALWA of 15%, 50%, and 100% and the addition of 0.75% steel fiber can reduce the density of concrete as much as 5%, 18%, and 26%, respectively, of the normal concrete. Meanwhile, the use of styrofoam ALWA of 15%, 50%, and 100% as well as the addition of 1.5% of steel fiber can reduce the density of concrete as much as 4.7%, 15.7%, and 25.5%, respectively, of the normal concrete.

The concrete mixture with 100% styrofoam ALWA without the addition of steel fiber and the concrete mixture with 100% styrofoam ALWA and 0.75% steel fiber can be included in the category of structural lightweight concrete. In accordance with the ASTM C330/C330M-17 [30], concrete can be categorized as structural lightweight concrete if its density is less than 1840 kg/m^3.

3.2. Failure and Crack Patterns

Based on the visual inspections, the crack and failure patterns of the specimens can be categorized into four types, i.e. columnar, shear, cone, and cone-shear types. The failure and crack patterns of the specimens without steel fiber and 0%, 50%, and 100% styrofoam ALWA replacement are the columnar type where vertical cracks started from the top and propagated downward to the bottom of the specimen. While the failure and crack patterns of the specimen with 15% styrofoam ALWA replacement are the cone-shear type where the cracks occurred diagonally. The failure and crack patterns of the specimens without steel fiber are shown in Figure 4.

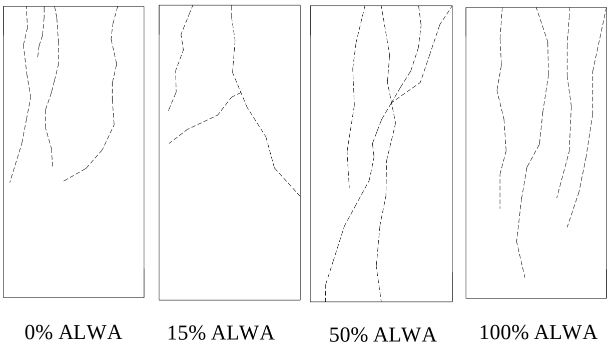

Figure 4. Failure and crack patterns of specimens without steel fiber and 0%, 15%, 50%, and 100% styrofoam ALWA replacement

The failure and crack patterns of the specimens with 0.75% steel fiber and 0%, 15%, and 50% styrofoam ALWA replacement are the columnar type where vertical cracks started from the top and propagated vertically downward to the bottom of the specimen until the maximum load. Whereas the failure and crack patterns of the specimen with 100% styrofoam ALWA replacement are the cone type where the cracks occurred diagonally in the mid-height region with the top and bottom remain unfailed. The failure and crack patterns of the specimens with 0.75% steel fiber are shown in Figure 5.

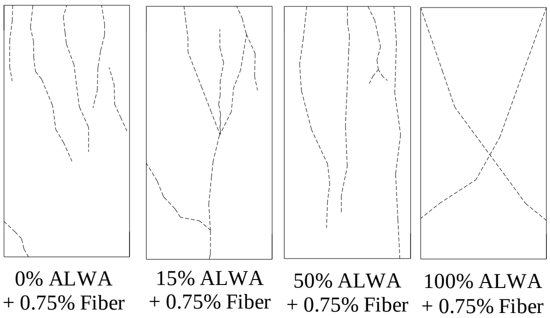

Figure 5. Failure and crack patterns of specimens with 0.75% steel fiber and 0%, 15%, 50%, and 100% styrofoam ALWA replacement

The failure and crack patterns of the specimen with 1.5% steel fiber and no styrofoam ALWA replacement are the cone-shear type where diagonal cracks started from the top and propagated downward to the bottom of the specimen. While the failure and crack patterns of the specimen with 15% styrofoam ALWA replacement are the shear type where the cracks occurred diagonally from side to side. For the specimens with 50% and 100% styrofoam ALWA replacement, the failures are the cone type. The failure and crack patterns of the specimens with 1.5% steel fiber are shown in Figure 6.

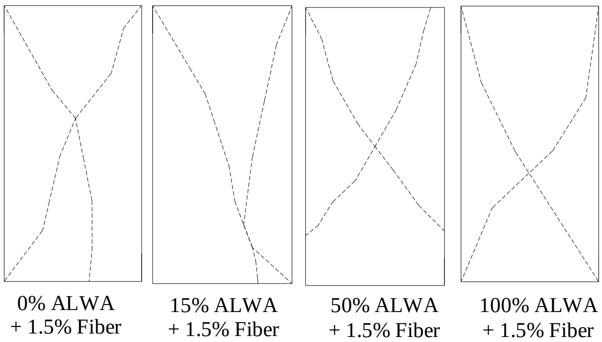

Figure 6. Failure and crack patterns of specimens with 1.5% steel fiber and 0%, 15%, 50%, and 100% styrofoam ALWA replacement

3.4. Compressive Strength Test Results

The concrete compressive strength tests were divided into three parts, i.e. concrete with styrofoam ALWA and 0% steel fiber, concrete with styrofoam ALWA and 0.75% steel fiber, and concrete with styrofoam ALWA and 1.5% steel fiber. The results of concrete compressive strength tests are tabulated in Table 8.

The concrete with styrofoam ALWA was capable of producing an optimum compressive strength of 22.5 MPa. However, the greater the percentage of styrofoam ALWA used as a substitution to the coarse aggregate, the lower the compressive strength of concrete. The reduction percentages of the compressive strengths of concrete with 15%, 50%, and 100% styrofoam ALWA were 33%, 55%, and 65%, respectively, of the normal concrete. The relationship between percentage of styrofoam ALWA and compressive strength of concrete can be seen in Figure 7.

Table 8. Compressive strength test results of concrete

Percentage of Styrofoam ALWA	Compressive strength, f_c' (MPa)		
	0% steel fiber	0.75% steel fiber	1.5% steel fiber
0%	33.5	36.3	42.1
15%	22.5	27.2	28.5
50%	15.0	19.4	26.1
100%	11.9	14.0	18.8

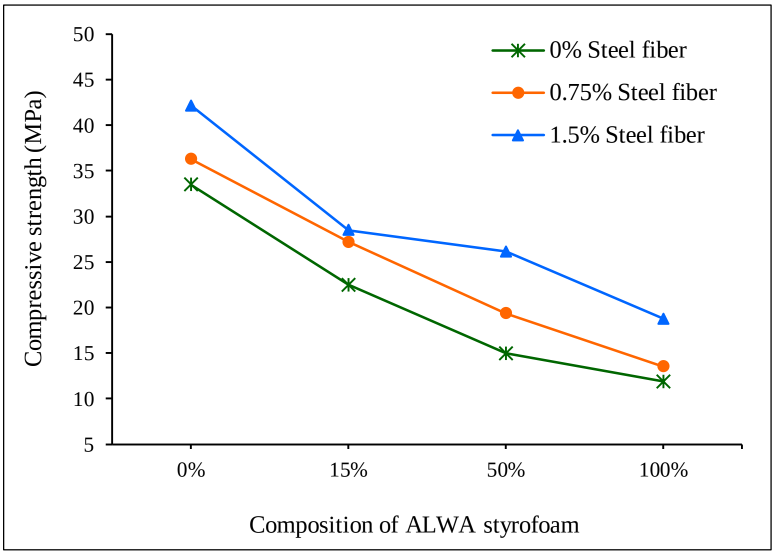

Figure 7. The relationship between percentage of styrofoam ALWA and compressive strength of concrete

One reason that caused the decrease of the compressive strength of concrete was that the styrofoam ALWA had the weak bond with the cement paste such that during the compressive strength tests the bond was separated apart from the cement paste as shown in Figure 8.

Figure 8. Concrete with substitution of styrofoam ALWA

In this study, the addition of steel fiber contributes significant impact to the compressive strength of concrete. The addition of 0.75% steel fiber in concrete with 15%, 50%, and 100% styrofoam ALWA was capable to increase the compressive strength as much as 21%, 29%, and 18%, respectively, compared to the concrete without steel fiber.

The presence of steel fiber affects the compressive strength of concrete. The more steel fiber added to the concrete mixture, the higher the compressive strength of concrete. However, the increase in compressive strength was not significant. The percentages of the compressive strength increase of concrete with the addition of steel fiber 1.5% and 15%, 50%, and 100% styrofoam ALWA were as much as 27%, 74% and 58%, respectively, of the concrete without steel fiber.

The compressive strength of concrete could increase since the steel fiber was able to withstand the concrete from cracking due to tensile stresses. The higher the percentage of steel fiber used in concrete, the greater the compressive strength of concrete. The ability of steel fiber to withstand the concrete from cracking due to tensile stresses can be seen in Figure 9.

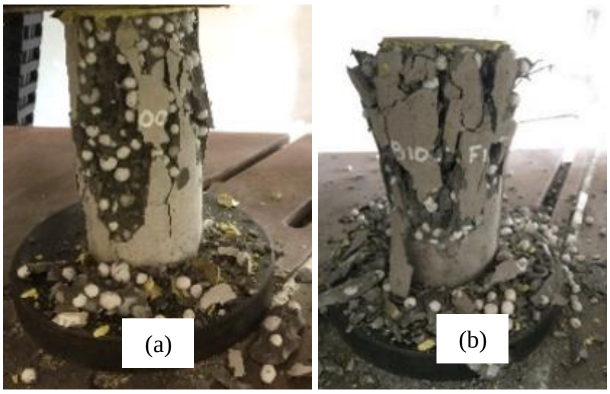

Figure 9. Condition of concrete specimens after the completion of the compressive tests: (a) concrete without steel fiber, and (b) concrete with steel fiber

The percentage of styrofoam ALWA used that was capable of producing the optimum compressive strength of concrete was at 15% replacement to the natural coarse aggregate. While, the optimum percentage of the steel fiber used that was able to increase the compressive strength of concrete was 1.5% of the total volume of concrete. The steel fiber used in this study is hooked end type.

The application of styrofoam ALWA of 15% in the concrete mixture was capable of producing an optimum compressive strength of about 22.5 to 28.5 MPa. In accordance with the ACI 318M-14 [31], the minimum compressive strength required for structural concrete should not be less than 17 MPa, whereas the minimum compressive strength required for the seismic-resistant concrete structures should be at least 21 MPa. Based on the results of the compressive strength tests, the concrete with styrofoam ALWA as the natural coarse aggregate replacement satisfied the requirements for both structural concrete and seismic-resistant concrete structures. The concrete without the addition of steel fiber requires about 19.5% styrofoam ALWA to achieve the compressive strength for seismic-resistant concrete structures of 21 MPa whereas to achieve the compressive strength for structural concrete only of 17 MPa, the use of styrofoam ALWA could be up to 37.5%. The relationship between the compressive strength of concrete and the percentage of styrofoam ALWA without steel fiber is shown in Figure 10.

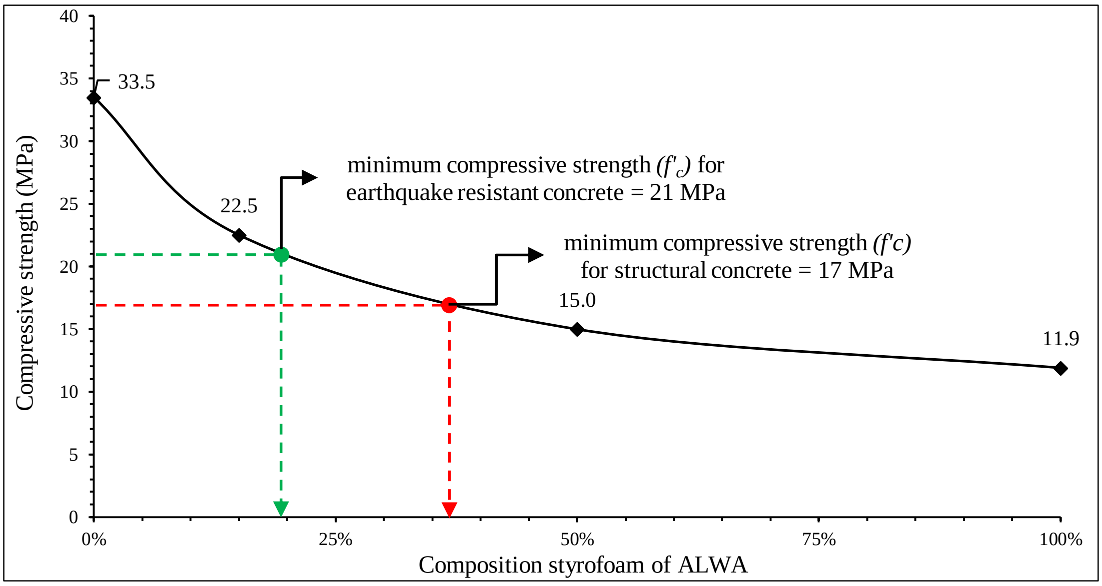

Figure 10. The relationship between the compressive strength of concrete and the percentage of styrofoam ALWA without steel fiber

The concrete with the addition of 0.75% steel fiber requires about 39.5% styrofoam ALWA to achieve the minimum requirement for structural concrete of 17 MPa [32, 33], whereas to achieve the minimum requirement of seismic-resistant concrete the styrofoam ALWA used could be up to 71.5% as a replacement to the natural coarse aggregate [34, 35]. The relationship of compressive strength of concrete and percentage of styrofoam ALWA with the use of 0.75% steel fiber is shown in Figure 11.

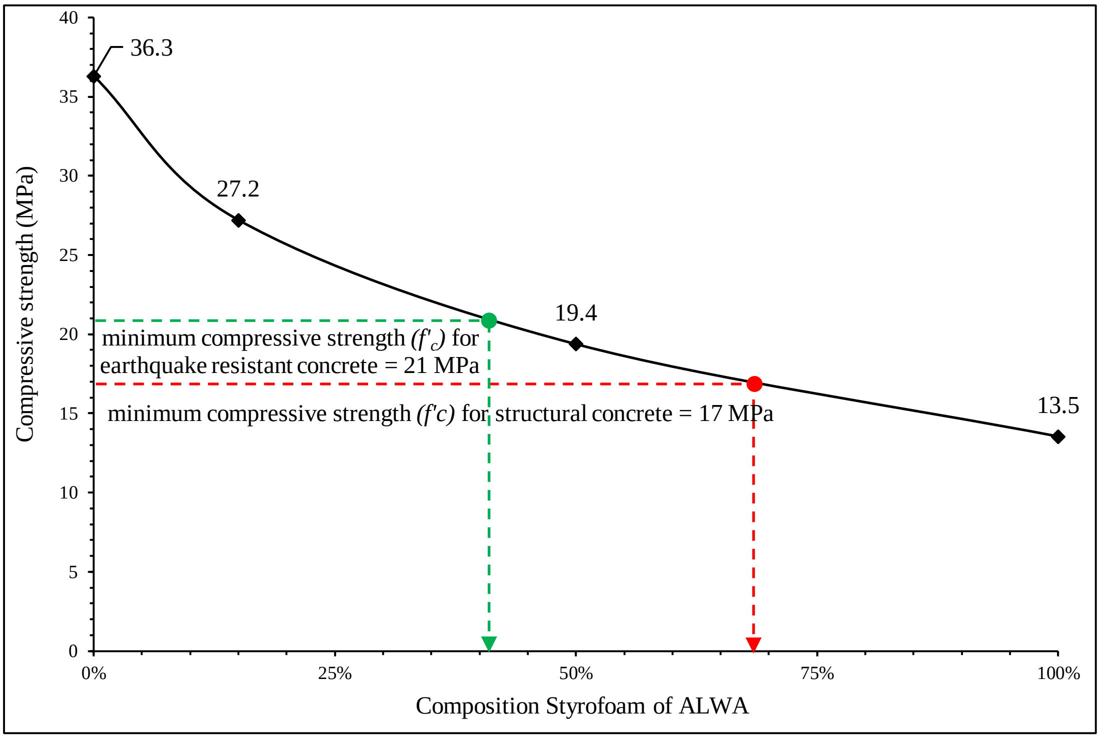

Figure 11. The relationship of compressive strength of concrete and percentage of styrofoam ALWA with the use of 0.75% steel fiber

Whereas, for concrete with the addition of as much as 1.5% steel fiber requires about 86.5% styrofoam ALWA to achieve the minimum compressive strength of structural concrete. In this study, the use of 100% styrofoam ALWA and 1.5% steel fiber could reach the compressive strength of concrete of 18.8 MPa such that it has exceeded the minimum requirement of compressive strength for structural concrete (17 MPa) [36, 37]. The relationship between compressive strength of concrete and percentage of styrofoam ALWA with 1.5% steel fiber can be seen in Figure 12.

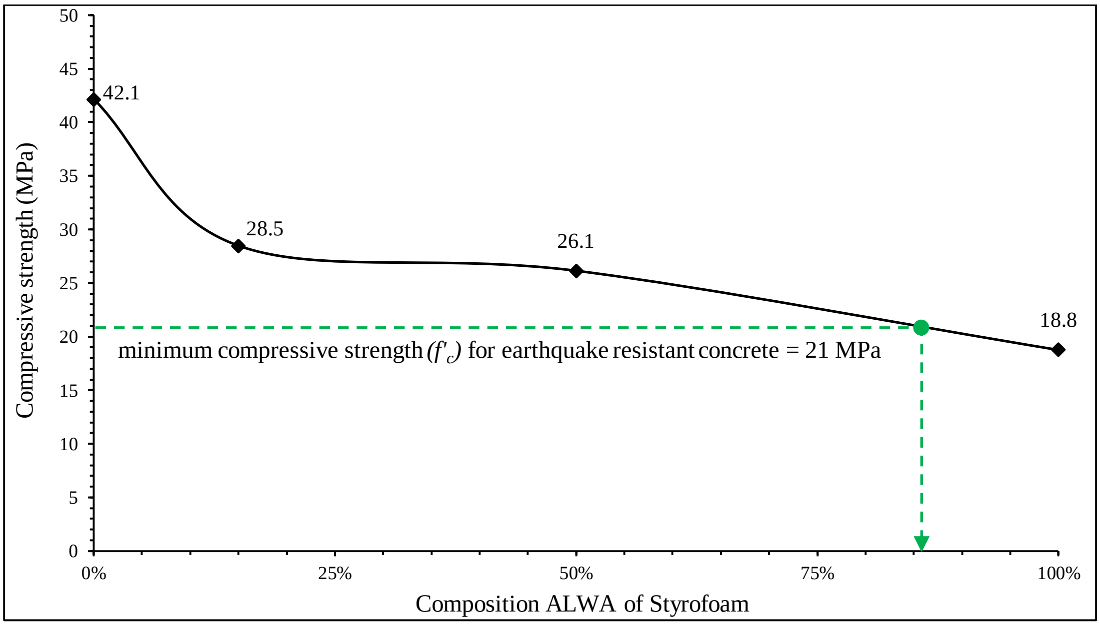

Figure 12. The relationship between compressive strength of concrete and percentage of styrofoam ALWA with 1.5% steel fiber

3.5. Modulus of Elasticity of Concrete

Modulus of elasticity of concrete is the ratio of the values of stress and strain. According to ACI 318M-14 [31], the modulus of elasticity of concrete can be obtained by dividing the concrete compressive stress at 45% of the concrete peak stress ($0.45f_c'$). The results of the calculation for the modulus of elasticity of concrete with styrofoam ALWA and steel fiber are given in Table 9.

Table 9. Modulus of elasticity of concrete

Percentage of Styrofoam ALWA	Modulus of elasticity of concrete, *Ec* (*MPa*)		
	0% steel fiber	0.75% steel fiber	1.5% steel fiber
0%	26,818	27,404	29,431
15%	21,213	23,231	23,495
50%	15,453	17,916	21,824
100%	12,924	13,591	16,047

Based on the calculation of the modulus of elasticity of concrete, it can be seen that the modulus of elasticity of concrete decreases with the addition of styrofoam ALWA. However, with the addition of steel fiber in the concrete with styrofoam ALWA, modulus of elasticity of concrete increases. The relationship between percentage of styrofoam ALWA used in concrete as a replacement to the natural coarse aggregate and modulus of elasticity of concrete is shown in Figure 13.

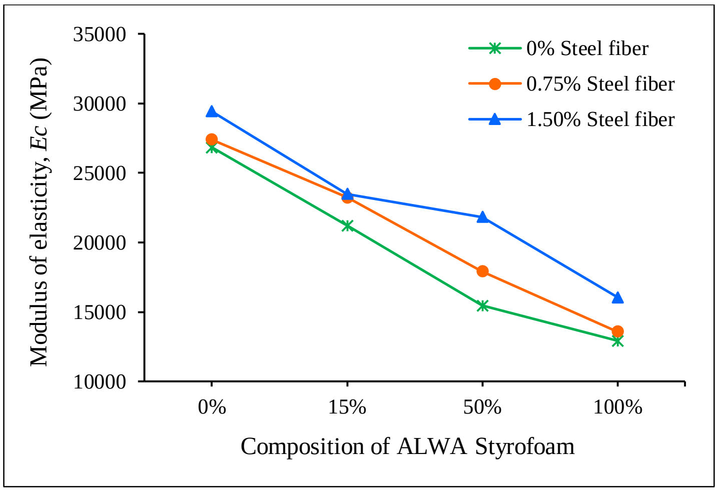

Figure 13. The relationship between percentage of styrofoam ALWA used in concrete as a replacement to the natural coarse aggregate and modulus of elasticity of concrete

The value of the modulus of elasticity of concrete (E_c) is directly proportional to the value of concrete compressive strength. The higher the value of concrete compressive strength, the higher the modulus of elasticity of concrete as well. The percentage of 15% styrofoam ALWA as a replacement to the natural coarse aggregate is capable of producing the optimum compressive strength of concrete. Thus, maximum elasticity modulus of concrete found about 23.495 MPa from the test was at the percentage of 15% styrofoam ALWA replacement and 1.5% steel fiber.

4. Conclusions

Based on the results of analysis and discussion on the above research, the following conclusions can be drawn:

- The use of styrofoam ALWA as a substitution to the natural coarse aggregate can reduce the density of concrete of about 5 to 35%.
- The presence of styrofoam ALWA in concrete that was capable of achieving the optimum compressive strength of concrete was about 15% replacement.
- The compressive strength of concrete with styrofoam ALWA decreases with the addition of styrofoam ALWA in concrete, but the steel fiber is able to prevent the concrete from cracking due to tensile stress, and thus, the compressive strength of concrete increases.
- The percentage of steel fiber that was capable of producing the maximum compressive strength was 1.5%.
- The modulus of elasticity of concrete is also found proportional to its compressive strength.

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